Flow Characteristics of a Pilot-Scale High Temperature, Short Time Pasteurizer*

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ABSTRACT

In this study, we present a method for determining the fastest moving particle (FMP) and residence time distribution (RTD) in a pilot-scale high temperature, short time (HTST) pasteurizer to ensure that laboratory or pilot-scale HTST apparatus meets the Pasteurized Milk Ordinance standards for pasteurization of milk and can be used for obtaining thermal inactivation data. The overall dimensions of the plate in the pasteurizer were 75×115 mm, with a thickness of 0.5 mm and effective diameter of 3.0 mm. The pasteurizer was equipped with nominal 21.5- and 52.2-s hold tubes, and flow capacity was variable from 0 to 20 L/h.

Tracer studies were used to determine FMP times and RTD data to establish flow characteristics. Using brine milk as tracer, the FMP time for the short holding section was 18.6 s and for the long holding section was 36 s at 72°C, compared with the nominal times of 21.5 and 52.2 s, respectively. The RTD study indicates that the short hold section was 45% back mixed and 55% plug flow for whole milk at 72°C. The long hold section was 91% plug and 9% back mixed for whole milk at 72°C. This study demonstrates that continuous laboratory and pilot-scale pasteurizers may be used to study inactivation of microorganisms only if the flow conditions in the holding tube are established for comparison with commercial HTST systems.

(**Key words:** pasteurization, milk, Foot-and-Mouth Disease, *Mycobacterium paratuberculosis*)

Abbreviation key: FMD = Foot-and-Mouth Disease, **FMP** = fastest moving particle, **Mptb** = *Mycobacterium paratuberculosis*, **RTD** = residence time distribution.

INTRODUCTION

Pasteurization is the process of heating every particle of milk or milk product in properly designed and operated equipment to a given temperature and holding at or above that temperature for at least the corresponding specified time (PMO, 2001). Pasteurization does not destroy all pathogenic microorganisms that may be present in milk, but it reduces the number of harmful microorganisms to a level at which they do not constitute a significant health hazard (Anon, 1993, 1994). Pasteurization standards in use today are based on the destruction of *Coxiella burnetii* (Holsinger et al., 1997).

In the US, milk usually is pasteurized commercially using HTST pasteurization. Flow conditions must be such that all particles of milk are held in the holding tube for a minimum of 15 s at a temperature of at least 72°C, with none leaving before the prescribed holding time (PMO, 2001). The holding tube length must be such that the fastest moving particle (**FMP**) time of any product will not traverse the holding tube in less than the required holding time. As pointed out by Hasting et al. (2001), the FMP from a microbiological safety viewpoint must be characterized, and this particle must receive at least the minimum defined pasteurization process. In this way, experimental conditions may be related to industrial practice.

A variety of laboratory methods developed to simulate the entire HTST pasteurization process have been used to determine the effectiveness of pasteurization for elimination of *Mycobacterium paratuberculosis* (**MPtb**) in milk. *Mycobacterium paratuberculosis* is the causative agent of Johne's Disease in dairy cattle and may be associated with Crohn's disease in humans. Experiments were carried out using the standard holder method (Grant et al., 1996), a simulated HTST method (Gao et al., 2002), and commercial HTST pilot-scale pasteurizers (Hope et al., 1997; Stabel et al., 1997). The pilot-scale pasteurizers have the advantage of simulating the come-up and cool down times of the larger commercial pasteurizers. The results from the studies were conflicting and were interpreted independent of parallel experiments to determine the FMP time for the experi-

mental apparatus that must be known for application to commercial-scale operations. Cerf and Griffiths (2000) suggested that reliable results on the effectiveness of pasteurization to eliminate MPtb in milk could only be accomplished by pasteurizing naturally infected milk using a commercial pasteurizer operated under turbulent flow. This is impractical in most situations though because of the large quantities of infected milk that would be required in experiments and other logistical problems.

The holding tubes of commercial HTST milk pasteurizers may be operated under laminar or turbulent flow conditions, which depend on the geometry of the tube, flow rate of the fluid, and the viscosity and density of the fluid. The Reynold's number, N_{Re}, frequently is used to distinguish the type of flow in the holding tube of a pasteurizer. It is defined by $N_{Re} = dv\rho/\mu$, where d is pipe diameter, v is the average velocity of the fluid flowing through the pipe, ρ is fluid density, and μ is fluid viscosity (Bird et al., 2002). The degree of pasteurization is rarely uniform for all portions of a product that pass through a pasteurizer (Rao and Loncin, 1974a) and depends on the FMP time and the residence time distribution (**RTD**) of particles flowing through it.

Hasting et al. (2001) calculated N_{Re} for holding tubes of several large-scale commercial HTST pasteurizers and compared them with the N_{Re}, calculated assuming long tube geometry, of the holding tubes of pasteurizers used in pilot-scale HTST pasteurization experiments for Mptb in milk (Hope et al., 1997; Stabel et al., 1997). The Reynold's number for the commercial holding tubes was well above 2100, indicative of turbulent flow for straight pipes, and appeared to approach plug flow conditions with $N_{Re} > 10,000$. The Reynold's number for the small-scale pasteurizer used by Stabel et al. (1997) was 400 and that used by Hope et al. (1997) ranged from 54 to 125 for a 12-mm i.d. tube. For flow in a long, straight pipe, these values are indicative of laminar flow. Even though flow was laminar by calculation of N_{Re}, Hope et al. (1997) and Stabel et al. (1997) reported inactivation of Mptb in artificially infected milk in most runs while Grant et al. (2000) showed that MPtb in naturally infected milk is capable of surviving commercial HTST pasteurization if present in raw milk in sufficient numbers.

However, N_{Re} is highly geometry dependent, and the use of the long, straight pipe assumption to calculate N_{Re} for the holding tubes of the pilot-scale pasteurizers may result in incorrect conclusions on the effectiveness of pasteurization for microorganisms in milk if the data are extrapolated to commercial HTST operation. The holding tubes of commercial pasteurizers are typically several meters long with bends at each end so that the whole assembly fits in as small a space as possible.

The assumption of straight pipe geometry is reasonably accurate for calculating N_{Re}. The newest pilot-scale pasteurizers typically have short helical tubes that can have the effect of secondary circulation, reducing the spread of residence times typically observed in laminar flow (Ruthven, 1971). The actual flow pattern through a process vessel, such as a pasteurizer and the holding tube, is between the plug flow and mixed flow ideals (Rao and Loncin, 1974a).

With the recent outbreak of Foot-and-Mouth Disease (**FMD**) in England, methods used to determine the effectiveness of pasteurization for elimination of FMD virus in milk have been reexamined (Tomasula and Konstance, 2004). Foot-and-Mouth Disease is not a public health threat but is highly contagious to cloven-hoofed animals. In studies conducted by Hyde et al. (1975), a simulated HTST method was used in which milk obtained from FMD virus-infected cows was heated to 72°C in bottles immersed in a constant temperature bath, held for 15 s, and then cooled. The FMD virus was not completely inactivated in the whole or skim milk samples. A later study (Walker et al., 1984) reported that the virus was inactivated at times >20 min and temperatures >100°C when a simulated HTST method was used and the temperature was 148°C for 2.5 s when a continuous flow UHT method was used. The thermal treatment that the infected milk samples received under pasteurization condition temperatures is difficult to ascertain from the data that were presented in both studies.

The objective of this study was to demonstrate a method for determination of FMP time and RTD of particles for a pilot-scale pasteurizer so that the thermal treatment that milk and any pathogens it may contain are known. This is in anticipation of conducting studies on HTST treatment of milk infected with FMD virus and other pathogens, including spore-forming pathogens, such as *Bacillus anthracis*. The method developed here is general enough for application to all pilot-scale HTST pasteurizers.

MATERIALS AND METHODS

HTST Pasteurization Equipment

Studies were made using the Armfield (Armfield, Inc., Denison, IA) FT74P/T HTST/UHT plate and frame heat exchanger equipped with nominal 15- and 45-s hold tubes. Figure 1 presents the physical arrangement of the process.

The process consists of a feed vessel mounted on a progressive cavity feed pump. The plate and frame heat exchanger is composed of a series of grooved plates that are arranged into sections for regeneration with heating and cooling of the solution. In operation, the
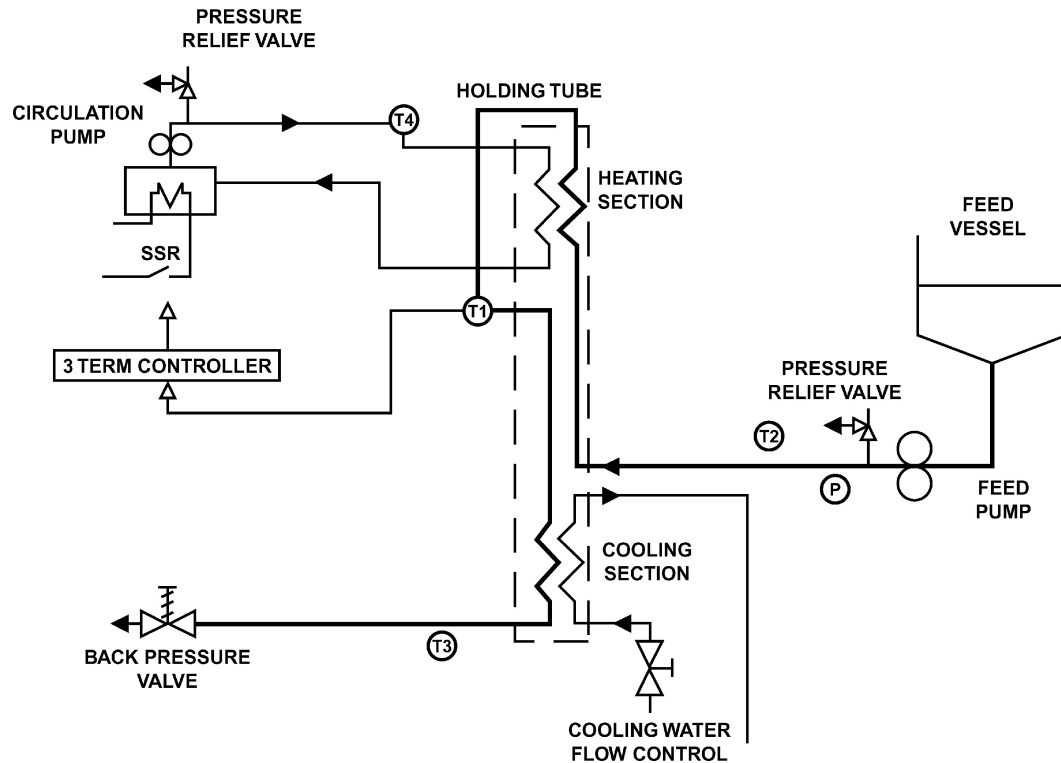
Figure 1. From process flow sheet, FT74P (Instruction manual; Armfield, Inc., Jackson, NJ).

test solution (water, milk, or brine) enters the raw side of the regenerator section of the HTST, contacting one side of the plates. The other side of the plates is heated by hot, pasteurized test solution leaving the holding tube, which is cooled as it transfers heat to test solution in the regeneration section (pasteurized-side of the regenerator). The preheated test solution then enters the heating section of the plate and frame heat exchanger. The other side of the plates is heated by hot water, which rapidly heats the preheated test solution to pasteurization temperature. A temperature of 72°C was used in the experiments. The test solution is then held in the holding tube for a time depending on flow rate and then enters the pasteurized-side of the regenerator, where it is cooled by the test solution entering the raw side. Finally, the pasteurized solution enters the cooling section of the HTST. Heating is computer controlled.

Holding Tubes

The test solution (water, milk, or brine solution) exits the plate and frame heat exchanger and enters a holding tube that is used to achieve the time-temperature requirements for pasteurization. The solution then returns to the cooling side of the pasteurizer via another flexible tube. This flexible tube contributes to the hold-

ing section. Two holding tubes were used in separate experiments: a short tube that is designated 15-s hold and a long tube that is designated 45-s hold by the manufacturer if flow rates of 9.87 and 18.97 L/h are used, respectively. The volume of the short 15-s hold tube is 35.7 mL plus 23 mL for the flexible tube (total = 58.7 mL). The volume of the long 45-s hold tube is 252.2 mL plus 23 mL for the flexible tube (total = 275.2 mL). The volume of the plate and frame heat exchanger is 114 mL. The pump volume, including a flexible tube connecting the pump to the pasteurizer, is 220 mL. A flow rate of 9.87 L/h was used to achieve a 15-s hold time for the short tube. The actual holding time for the 15-s hold tube is then obtained by dividing the volume of the hold tube plus the volume of the flexible tube section by the flow rate or 21.5 s. The flow rate used for the 45-s hold tube was 18.97 L/h, and the actual holding time is 52.2 s. The diameter of both holding tubes is 9.65 mm. The flow rate was determined by a linear calibration of the pump flow rate as a function of the pump setting. The value of the correlation coefficient, r, was 0.99.

Test Solutions

The brine water test solution was prepared by dissolving 200 g of NaCl in 1000 mL of deionized water

(3.5 *M*). The brine milk test solutions were prepared by dissolving approximately 14 g of NaCl in 2000 mL (0.12 *M*) of locally purchased whole milk until the conductivity was in the range of 12 to 13.5 mS. The solutions were allowed to sit for approximately 30 min prior to experiments. Conductivity was determined using a TDSTestr 20 conductivity meter (Cole Parmer Instrument Co., Niles, IL). The added Na ion exchanges with Ca in the milk (Famelart et al., 1999). Most of the exchange happens quickly (diffusion controlled), but the residual exchange creates a small amount of instability in the conductivity readings.

Determination of FMP and RTD

The method reported here uses a tracer method for determination of the FMP in which the brine solution is directly fed into the pasteurizer. In a typical experiment, water (or milk) is pumped through the system until steady state is reached. When the surface of the feed is just observed at the inlet to the pump, a sudden step change is introduced to the system by pouring the tracer solution into the feed funnel.

Brine water samples were collected in 4.5-mL (nominal) glass vials as the stream exited the holding tube and the flexible tubing that would be connected to the cooling section during an actual pasteurization run. Twenty vials were used in all. Two were used for the tracer control samples. The other 18 samples were collected continuously to ensure collection of zero or first particle samples. After all samples were collected, the tracer solution was allowed to drain into the pump, and the feed funnel was filled with fresh test fluid, water, or milk to begin the next experiment. The system was purged until the conductivity of the exit fluid indicated no elevated salinity. Experiments were performed in duplicate.

Brine milk samples were collected in 10-mL (nominal) glass vials. Seventeen vials were used. Two extra vials were used for the tracer control samples, and one extra vial was used for a zero or initial milk sample. The 17 samples were collected continuously.

After all samples were collected, the tracer solution was allowed to drain into the pump, and the feed funnel was filled with fresh test milk. The system was purged until the conductivity of the exit fluid indicated no elevated salinity.

Time for each vial for the FMP time study was determined as the time the vial first started to fill with sample. Time for each vial for the RTD study was determined as the median time the vial filled with sample.

To complete the RTD study, the previously described procedure was repeated, collecting brine water or milk samples leaving the pump. Then, samples were col-
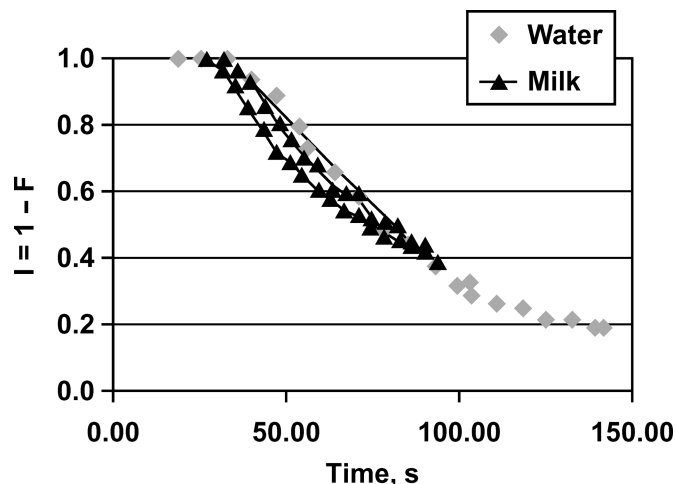

Figure 2. Resistance time distribution plotted as internal age distribution function, I, versus time at 9.87 L/h.

lected leaving the pump followed by the plate and frame heat exchanger.

To determine the change in conductivity of the water samples, each sample was poured into a test beaker. The sample vial was filled with fresh tap water and added to the sample. The dilution had the effect of cooling the sample and achieving a sufficient volume of liquid to measure conductivity. All samples were treated identically, and it was the change in conductivity that was used so that there were no effects caused by this dilution. Conductivity of the milk samples was determined as is because there was sufficient volume to test.

RESULTS AND DISCUSSION

FMP Determination

Levenspiel (1972, 1999) presents an excellent treatise on determination of FMP and RTD in chemical processing equipment that is followed here with some modification. A discussion on determination of RTD specific to continuous pasteurization is also presented in Rao and Loncin (1974a,b). In the discussion that follows, the pasteurizer and its associated holding tube is considered a type of chemical reactor.

The tracer data obtained using the brined water and milk samples are used to calculate values of F, the ratio of brine concentration leaving the holding tube divided by the initial concentration of brine in the sample stream, at each sampling time, for the flow rates of 9.87 and 18.97 L/h. Values of F were also calculated for the fluid leaving the pump, the pump plus the plate and frame heat exchanger, and the pump plus the plate and frame heat exchanger and the holding tube. The F
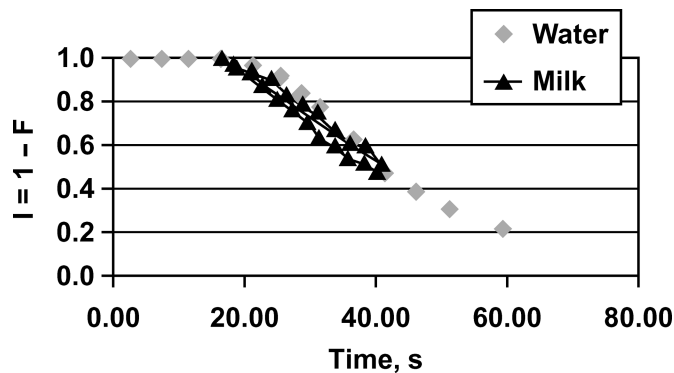
Figure 3. Resistance time distribution plotted as internal age distribution function, I, versus time at 18.97 L/h.

values were then used to calculate the internal age distribution (Levenspiel, 1972, 1999), where I = 1 − F and represents the age of particles still in the equipment.

Figures 2 and 3 plot the internal age distribution function, I, as a function of time for the 2 flow rates. The curve represents the downstream response of the process to the upstream step change in input with addition of brine solution. The curve ranges between 0 and 1. The time for the first particle exiting the process corresponds to the intercept at I = 1. Some preliminary RTD data (not shown) were interpolated to establish approximately when the RTD curve would break, namely, when the value of I dropped below 1.0. Then, the reported RTD data were collected in the proper range so the samples collected would include the first particle. Interpolation of the RTD curves confirmed the validity of the first particle values.

Table 1 presents the results for the first particle analysis and the correlation coefficients for the section of

the RTD curves with a negative slope. These RTD curves were used to confirm the accuracy of the first particle value. The first 2 rows, pump and pump + plate and frame heat exchanger, present the times for the first particle to exit when no hold tube is used. Two flow rates were used, corresponding to the flow rates used to obtain the nominal holding time indicated for the each hold section: 21.5 s for the short hold section and 52.2 s for the long hold section. Both flow rates were used for both short and long sections, although usually the low flow rate would normally be used only for the short hold section and the higher flow rate would normally be used only for the long hold section. We only discuss the appropriate flow rate and hold section combination but list all data in this paper for information purposes.

At the lower flow rate of 9.87 L/h, adding the short hold section (15-s hold tube and flexible tube), the residence time for the first particle in water increased from 48 s for the pump and pasteurizer alone to 70 s for the combination, a difference of 22 s. Therefore, the first particle hold time with water for the short hold section was 22 s compared with the nominal value of 21.5 s. For milk, the first particle time was 18.6 s or (68 to 49.4). When the long hold section (45-s hold tube and flexible tube) replaced the short hold section and the flow rate was increased, the first particle time using water increased from 28 s with no hold section to 62.4 s for the combination. The difference is 34.4 s, the first particle time for water. For milk, the first particle time is 36 s.

If N_{Re} is calculated assuming that the hold tubes are approximated by a long, straight pipe geometry (Hasting et al., 2001), then N_{Re} is approximately 170 for the short hold tube and 330 for the long hold tube. Therefore, because the N_{Re} for both tubes indicates lam-

Table 1. First particle exit times for each specified unit of the pasteurizer.

Exit location	9.87 L/h			18.97 L/h		
	Nominal residence time	First particle time		Nominal residence time	First particle time	
		Milk	Water		Milk	Water
			(S)			
Pump	80.2	28 (0.98)[1]	30 (0.99)	41.8	13 (0.97)	12 (0.99)
Pump + PFHE[2]	121.8	49.4 (0.98)	48 (0.99)	63.4	27 (0.95)	28 (0.97)
Pump + PFHE + short hold section	143.3	68 (0.93)	70 (0.99)	74.6	33 (0.97)	35.6 (0.99)
Pump + PFHE + long hold section	222.1	121 (0.98)	122 (0.96)	115.6	63 (0.98)	62.4 (0.99)
Short hold section	21.5	18.6	22.0	11.2	6.0	7.6
Long hold section	100.3	71.6	74.0	52.2	36.0	34.4

[1]Correlation coefficients for linear regression of the back-mixed curve are presented in parentheses.

[2]PFHE = Plate and frame heat exchanger.

Figure 4. Resistance time distribution plotted as internal age distribution function, I, versus reduced time at 9.87 L/h.
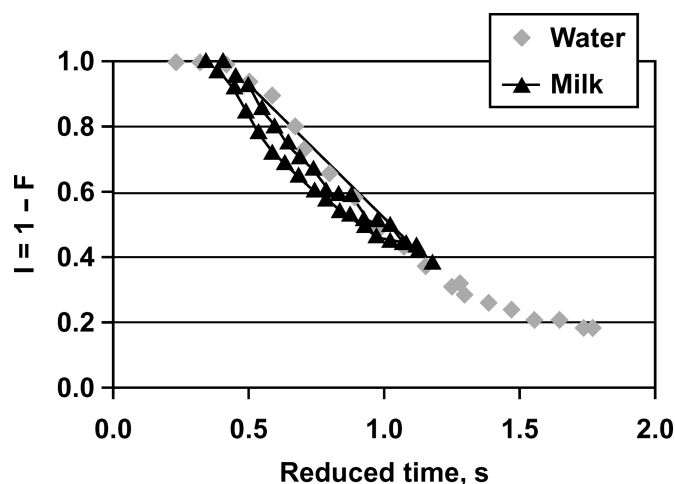

Figure 5. Resistance time distribution plotted as internal age distribution function, I, versus reduced time at 18.97 L/h.

inar flow, the FMP would be one-half of the nominal or average residence time. For the short hold section at the lower flow rate of 9.87 L/h, this would be 0.5×21.5 s or 10.8 s, compared with a value of 18.6 s obtained by FMP analysis, and for the long hold section at the higher flow rate of 18.97 L/h, this would be 0.5×52.2 s or 26.1 s compared with a value of 36 s. This confirms that N_{Re} is not a valid predictor of the FMP time and RTD in the hold tubes.

RTD

Flow through the plate and frame heat exchanger of the pasteurizer and hold tubes is most likely a combination of plug and back-mixed flow with a small component of undefined flow. More important is knowledge of how long the individual molecules reside in the plate and frame heat exchanger and hold tubes or the distribution of residence times in the flowing fluid (Levenspiel, 1999).

Grijspeerdt et al. (2003) used computational fluid dynamics to study the hydrodynamics of milk flow in plate heat exchangers. Their analysis elucidated the movement of flow regimens between the walls and bulk fluid flow. It also indicated areas most prone to fouling. Computational fluid dynamics showed that the influence of the inlet flow extends only up to 3 corrugations. Therefore, we can safely assume the flow leaving the plate heat exchanger and entering either the short or long hold section of our pasteurization equipment has reached a steady-state defined flow. A RTD study of the hold sections should be independent of the plate heat exchanger.

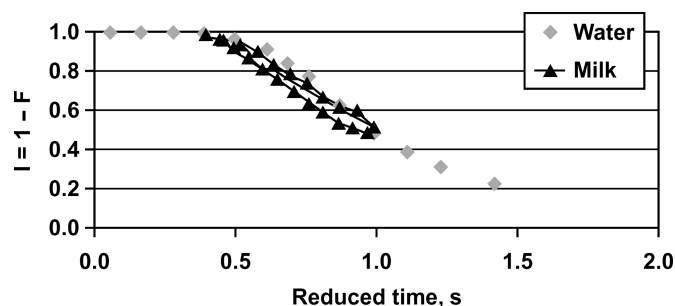Therefore, the RTD was determined for the plate and frame heat exchanger with no hold section and then with each hold section. The volume fractions of plug and back-mixed flow in the pasteurizer without any hold section plus with each hold section was also determined.

Figures 4 and 5 plot the internal age distribution function, I (Levenspiel, 1999), as a function of the dimensionless term, reduced time, defined as sample time divided by the nominal residence time for the 2 flow rates. Table 2 presents all of the results of the RTD analysis normalized as fraction of back-mixed and plug flow through the entire system to the exit of the section noted. Table 1 included the correlation coefficient for the back-mixed section of the curve (negative slope). However, a better estimate for the error of the RTD data is the amount of normalization required. Table 2 includes the normalization factor or summations of the fractions of back-mixed and plug flows before normalization. It must be kept in mind that a very small error in the slope of the curve has a large effect on the overall results. Errors of 10 to 15% are common. The 2 flow rates, 9.87 and 18.97 L/h, corresponding to the flow rates used to obtain the nominal residence time indicated for the each hold section (21.5 s for the short hold section and 52.2 s for the long hold section) were used.

As with the FMP analysis, we will only discuss the appropriate flow rate and hold section combination. The first 2 rows (Table 2) present the volume fraction when no hold section was used. A flow rate of 9.87 L/h was used with the short hold section, and 18.97 L/h was used with the long hold section. With no hold tubes, the normalized volume fractions at low flow rate out of the plate and frame heat exchanger were 0.44 plug flow and 0.56 back-mixed flow for water and 0.49 plug flow and 0.51 back-mixed flow for milk. With no hold section, the normalized volume fractions at high flow rate out of the plate and frame heat exchanger were 0.49 plug flow and 0.51 back-mixed flow for both water and milk.

Using the short hold section and low flow rate, the normalized volume fractions were 0.53 plug flow and

Table 2. Residence time distribution analysis normalized as fraction of type of flow through the entire system to the exit of the section noted. V_b = volume of back-mixed flow, V_p = volume of plug flow, and NF = estimated experimental error expressed as the factor used to normalize the data.

| | 9.87 L/h | | | | | | 18.97 L/h | | | | | |
| | Milk | | | Water | | | Milk | | | Water | | |
Exit location	V_b	V_p	NF	V_b	V_p	NF	V_b	V_p	NF	V_b	V_p	NF
Pump	0.71	0.29	1.17	0.65	0.35	1.13	0.68	0.32	1.22	0.58	0.42	0.94
Pump + PFHE[1]	0.51	0.49	0.89	0.56	0.44	0.93	0.51	0.49	0.94	0.51	0.49	0.93
Pump + PFHE + short hold section	0.50	0.50	1.00	0.47	0.53	1.01	0.50	0.50	0.88	0.46	0.54	0.94
Pump + PFHE + long hold section	0.37	0.63	0.89	0.43	0.57	0.97	0.32	0.68	0.84	0.28	0.72	0.81

[1]PFHE = Plate and frame heat exchanger.

0.47 back-mixed flow for water and 0.50 plug flow and 0.50 back-mixed flow for milk. The normalized volume fractions using the long hold section and high flow rate were 0.72 plug flow and 0.28 back-mixed flow for water and 0.68 plug flow and 0.32 back-mixed flow for milk. The milk and water data agree within 5% error.

These data were used to calculate the volume corresponding to plug and back-mixed flow through the various parts of the process. The difference between the volumes through a section minus the volumes through the previous section indicates the normalized volume fraction for the specific section. For instance, using milk with a flow rate of 9.87 L/h and short hold time, plug flow accounted for 196.5 mL. (0.50 × 393 mL). Back mixed flow accounted for 196.5 mL. There was a 165-mL plug flow and a 169-mL back-mixed flow from the pasteurizer. The difference gives the specific volumes corresponding to the short hold section, 32 mL plug and 27 mL back mixed.

With the volume specific to each section, the volume fraction of each type flow for each section starting with the plate and frame heat exchanger was calculated. Table 3 presents these data. It is noteworthy that milk flow was >80% plug flow in the long hold section at both flow rates. Water was >72% plug flow in all cases. However, the milk was only 55 to 56% plug flow in the short hold section.

The N_{Re} for the plate and frame heat exchanger, where $NRe = D_e v \rho / \mu$, where D_e is the equivalent diameter and is equal to $2 \times$ the gap between the plates, is 75 for the lower flow rate of 9.87 L/h and is 150 at the higher flow rate of 18.97 L/h. For plate heat exchangers, the turbulent zone for N_{Re} is between 10 and 400.

At steady state, the composition of product or test fluid entering the hold section will be equal to that in the feed. The fluid is heated to the pasteurization temperature during come-up time in the plate and frame heat exchanger pasteurizer, but only the hold time is used to determine thermal treatment. Analysis of the pasteurization process is specific to the hold section consisting of the hold tube and the tube connecting the hold tube to the cooling side of the pasteurizer.

Calculation of D Values Obtained from Small-Scale HTST Pasteurization Experiments

Models for first-order inactivation kinetics are more complex when based on the fractions of plug flow and back-mixed flow determined by RTD studies. These models are presented in detail in Levenspiel (1972, 1999) and Rao and Loncin (1974b). The models are mathematically challenging, but charts are presented in Levenspiel (1972, 1999), simplifying their use. However, D must be interpreted with extreme care, because it is not only a function of temperature but can also be a function of growth medium used and heating menstruum with respect to both pH and composition as

Table 3. Residence time distribution normalized as fraction of type of flow for each specific unit. V_b = volume of back-mixed flow and V_p = volume of plug flow. Estimated experimental error expressed as the factor used to normalize the experimental data is presented in Table 2.

| | 9.87 L/h | | | | 18.97 L/h | | | |
| | Milk | | Water | | Milk | | Water | |
Exit location	V_b	V_p	V_b	V_p	V_b	V_p	V_b	V_p
PFHE[1]	0.12	0.88	0.39	0.61	0.18	0.82	0.35	0.65
Short hold section	0.45	0.55	0	1.0	0.44	0.56	0.20	0.80
Long hold section	0.20	0.80	0.28	0.72	0.092	0.908	0.0	1.0

[1]PFHE = Plate and frame heat exchanger.

demonstrated for *Pediococcus* sp. (Annous and Kozempel, 1998).

It is recommended that instead of calculating D values through assumption of first-order kinetics and using the models referenced above for HTST pasteurization, that experiments be conducted in flow equipment to ensure that the destruction of the organism occurs at times greater than or equal to that of the FMP to establish the minimum holding time necessary for destruction of the microorganism. In this way, the exact time it takes to either reduce the numbers of a microorganism or eliminate it completely may be determined.

CONCLUSIONS

Tracer analysis was used to characterize a pilot-scale HTST pasteurizer to determine the FMP time and RTD for whole milk and water. This analysis must be applied to any flow-type experimental pasteurization equipment so that the thermal process delivered to milk is accurately quantified and interpreted. While the turbulent flow conditions typically encountered in commercial pasteurization are thought desirable for lethality studies conducted at the laboratory level, they are not necessary as long as conditions in the experimental flow reactor are understood, i.e., FMP time and RTD studies have been conducted.

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